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DESIGN OF A REFUELING TANKER DELIVERING LIQUID HYDROGEN

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Abstract

A refueling tanker that could deliver 155,000 lb of liquid hydrogen to a hypersonic tanker in 15 min was designed. A flying boom system was chosen to fit strict delivery criteria. Tank design and material specification were also addressed. To assure the flow required, it was important to cancel the pressure drop phenomenon. Geometry, aerodynamics, weight considerations, propulsion, stability, and performance for the tanker were also considered. Finally, the cost of developing three prototypes was estimated.

Introduction

Ecole Polytechnique Fèminine designed a refueling tanker to deliver liquid hydrogen to a hypersonic aircraft designed by a team from the Ohio State University.

The aircraft had to comply with the following requirements:

Refueling altitude	40,000 ft
Refueling Mach number	M = 0.8
Fuel transferred	155,000 lbs of liquid hydrogen (LH_2)
Range to rendezvous	2000 Nm
Total range	4500 Nm
Time spent refueling	15 min
Maximum take-off and landing runway distance	14,674 ft

In order to choose an appropriate aircraft to carry out such a mission, it was important to know the characteristics of the LH_2 tanks. Once the dimensions (particularly the weight and the length) were known, we were then able to design the aircraft. It is for this reason that the first part of this paper deals with the refueling system and the liquid hydrogen tanks, whereas the second part presents the characteristics of the aircraft (geometry, weight estimation, aerodynamics, performance, mission).

The Refueling System

There are two principal types of refueling systems:

- The probe and drogue system consists of a long flexible tube ending in a mesh covered cone. This system enables simultaneous refueling of up to three aircraft at the same time, but the flow rate is rather low.
- The flying boom system consists of a telescopic extension that is guided into the receiving aircraft's refueling receptacle. This system allows a higher flow in the boom.

As our aircraft has to deliver 155,000 lb of fuel in 15 minutes and since the density of the LH_2 is 4.42 lb/ft^3, we chose to use a flying boom.

Calculation of the pressure drop

Once the refueling system was chosen, we had to evaluate the pressure drop in the system in order to find the pressure of the LH_2 tanks.

Our calculation was based on the comparison with the KC-10's pressure drop:

$$\Delta P = 2.84 \text{ bars}$$

LH_2 tanks

Table 1 gives the dimensions of the three tanks.

Table 1 Tank dimensions

	Diameter	Length	Volume
Tank 1	11.48 ft	49.21 ft	5,085 ft^3
Tanks 2 and 3	19.68 ft	49.87 ft	15,183 ft^3

The shapes of the tanks are depicted in Figure 1.

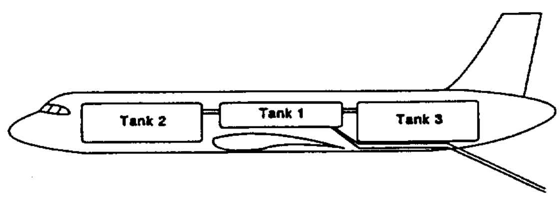

Fig. 1 Refueling tanks

The tanks were made of Al 2219; because of the temperature of the LH_2 (20° K), they were insulated with polyurethane foam. Tank weights are shown in Table 2.

Table 2 Tank weights

	LH_2 (lb)	Al 2219 (lb)	Insulation (lb)
Tank 1	22,480	4,011	2,292
Tanks 2 and 3	67,000	11,990	2,369

To assure the flow required, it was important to cancel the pressure drop phenomenon. The tanks were insulated so that the pressure inside them would rise naturally from 1 bar (initial pressure of the LH_2 when filling the tanks) to 1.5 bar (pressure needed in the tanks of the refueled aircraft). We injected gaseous hydrogen to assure the rise from 1.5 bars to 4 bars (1.5 + 3 bars of pressure drop). In order to obtain this gaseous hydrogen, a small quantity of LH_2 was heated before going through a compressor.

Main Aircraft Characteristics

Geometry

A three-view of the aircraft is depicted in Figure 2. The main dimensions of the aircraft include 1) a wing area of 7,750 sq ft, 2) wing span of 268.47 ft, 3) length of 252.95 ft, and 4) fuselage width and height of 22.96 ft.

Aerodynamics

The aerodynamic coefficient was calculated and plotted in Figure 3, which shows drag vs lift.

Weight estimation

Weight estimation utilized a method from Aerospatiale. The weight estimates shown in Table 3 include an assumption that the structural weight would be reduced about 5 per cent in the next ten years.

Table 3 Aircraft weight estimation

Glider	352,888 lb
Propulsion	62,924 lb
All mission accommodations	18,424 lb
Accommodations according to mission	54,023 lb
Crew	750 lb
Fuel	405,116 lb
Variable payload	155,000 lb
MTOW	848,765 lb
EW	448,655 lb

Propulsion

Our aircraft has four engines, each with a nominal thrust of 57,000 lbs. Three engines are suitable: 1) Pratt & Whitney PW 4000, 2) Rolls Royce RB 2111, or 3) General Electric CF6-80 C2.

Stability

The stability of an aircraft depends on the position of the center of gravity compared to the aerodynamic center. To insure stability, the center of gravity should be in front

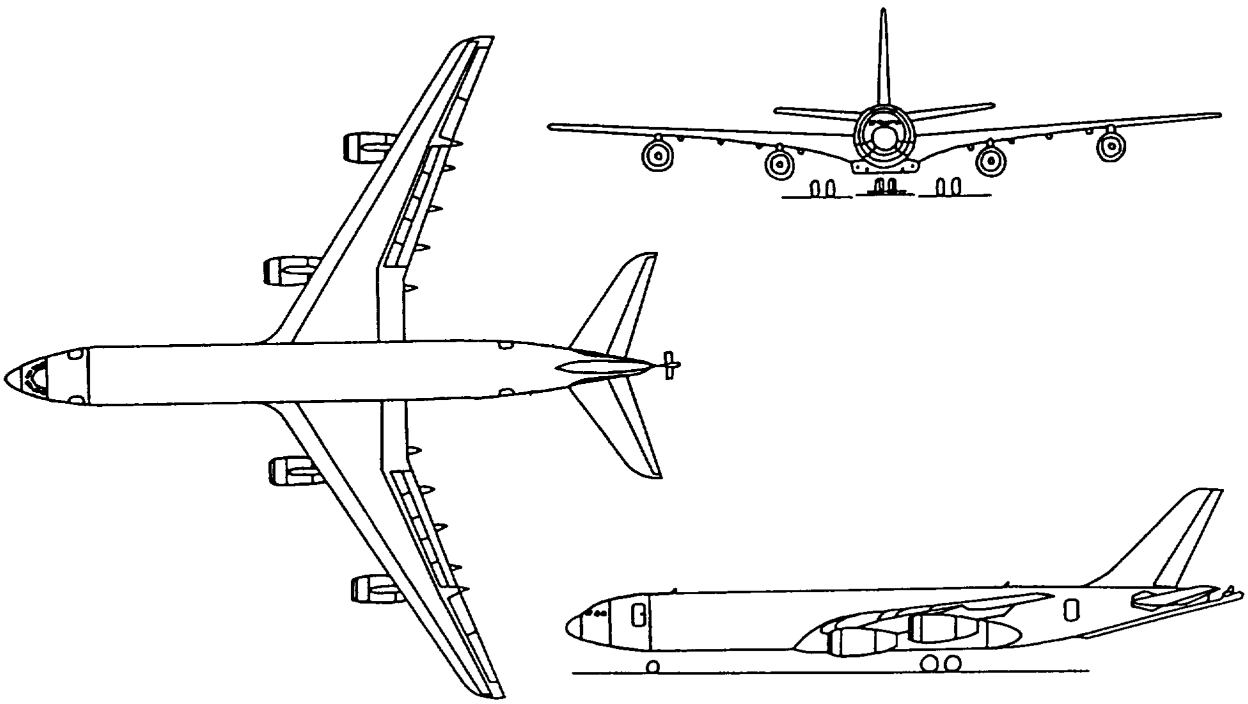

Fig. 2 Three-view of the refueling tanker

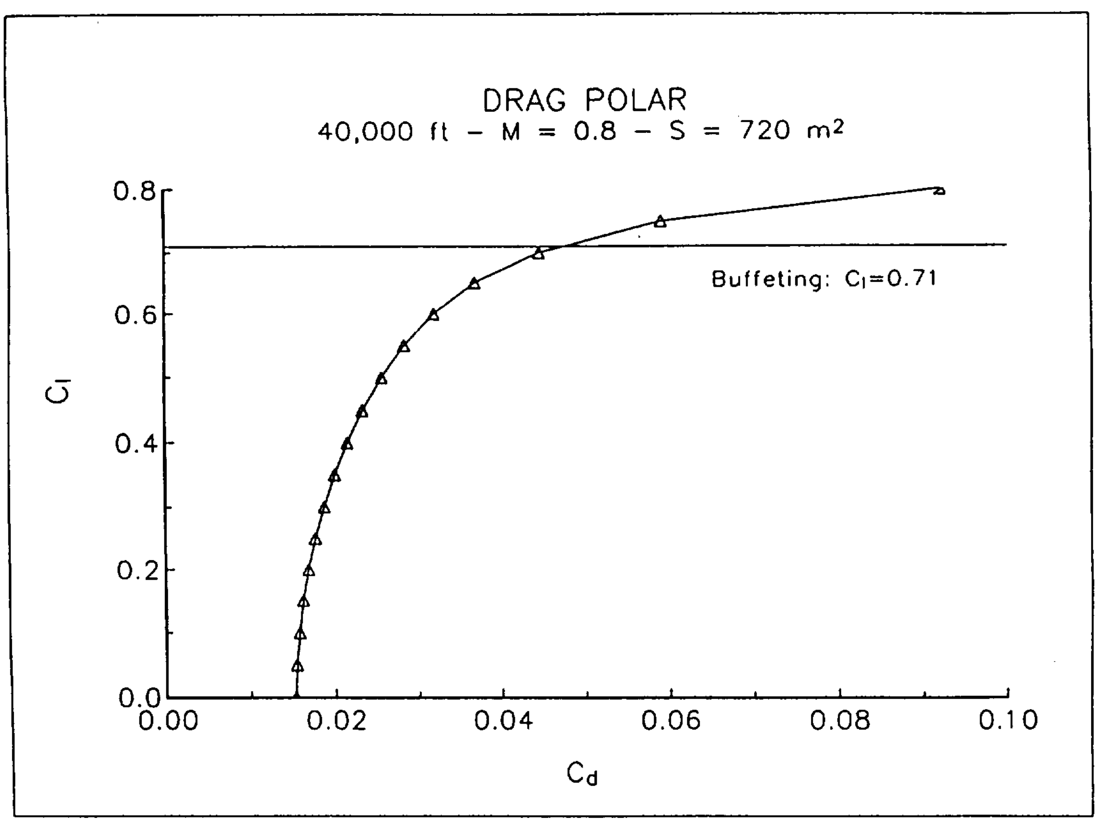

Fig. 3 Calculation of the drag polar

of the aerodynamic center by 10%. The aerodynamic center was calculated to be at 134.77 ft using a method from Aerospatiale. The cener of gravity of the aircraft was estimated b ased on component weights and locations; the c.g. was calculated to be 130.77 ft from the nose of the aircraft.

This puts the relative position of the center of gravity from the aerodynamic center at 10.51%. In order to obtain this value, the wings of the aircraft must be placed at 55% of the length of the cabin.

Aircraft Performance

The refueling aircraft must travel a distance of 2000 Nm at an altitude of 40,000 ft and a cruise Mach number of 0.8 to deliver 155,000 lbs of liquid hydrogen to a hypersonic aircraft in less than 15 minutes. These strict performance requirements are presented in Figure 4.

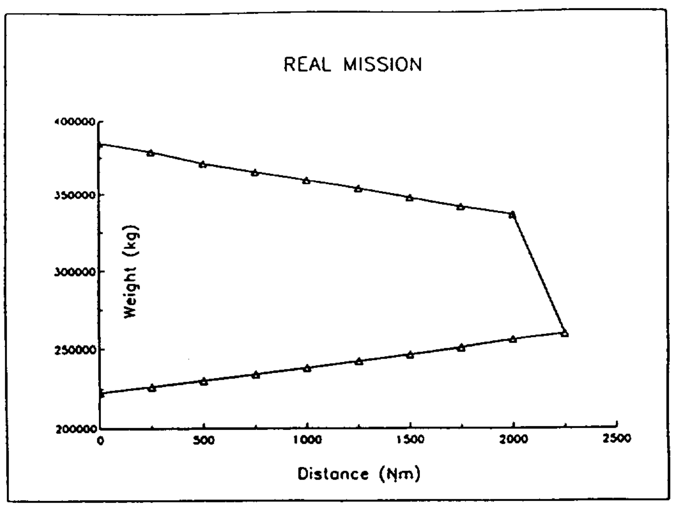

Fig. 4 Real mission profile

Conclusion

The optimal aircraft designed by the EPF team has the following characteristics:

Wing area	7750 sq ft
Wing span	268.47 ft
MTOW	848,765 lb
Payload	155,000 lb
Nominal thrust	57,000 lb
Mach	0.8
Ceiling	40,000 ft

Compared to existing civil aircraft, our tanker has a wing area 1.5 times that of the Boeing 747. This factor of 1.5 is due to the requirement of reaching 40,000 ft after having flown 2000 Nm.

We could have chosen to design two smaller aircraft to do the refueling simultaneously, but the tendency in the aircraft world is to design larger aircraft with bigger payloads. Further, we can imagine that in a few years refueling aircraft may become supersonic or even hypersonic. We estimate that it would cost $38 billion to develop three prototypes of our aircraft.